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EXPERIMENTS ON THE PROTECTION OF STEEL AND ALUMINUM EXPOSED TO SEA WATER.

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WITH DISCUSSION.

In February, 1895, the author, by permission of the Navy Department, suspended a cage containing twenty iron plates coated with various preservative coatings in the sea water in the Brooklyn Navy Yard. At the expiration of six months it was found that by some accident the cage and all the plates had been lost. Arrangements were then made for another and more carefully conducted test, and in making these arrangements the author was assisted by Naval Constructor F. T. Bowles, to whom he takes this opportunity of expressing his appreciation and thanks. Without his co-operation it would have been impossible to carry out the experiments. The work of preparing and applying the coatings was done by Edward Smith & Company, of New York City, who paid all the expenses incident to the whole work, and the aluminum plates were furnished free of charge by the Pittsburgh Reduction Company.

It was desired especially to learn the protective capacity of various varnishes and of what are known as enamel paints, which are pigments ground in varnish.

The ordinary oil and resin varnishes are made by compounding certain resins (of which those selected for these experiments are Kauri, Zanzibar and Manilla, and the resinous mineral known as gilsonite) with various proportions of refined linseed oil, and these oil and resin compounds are then thinned with spirit of turpentine, which is commonly regarded as a vehicle, so that the essential differences in varnishes are due chiefly to the kinds of resin used and the proportion of oil. For convenience, it is customary to assume 100 lbs. of resin as the unit, and with this compound 8 galls. of oil for one kind of varnish, or 12 galls. for another, or 20 galls. for another, or 30 galls. for another; and it was believed that for the purpose of these experiments these four types of varnishes, commonly spoken of as 8, 12, 20 and 30-gall. varnishes, were sufficient. It was also regarded as desirable to know what resins were most suitable; hence there were prepared such series of varnishes from Kauri, Zanzibar and Manilla resins, and an 8-gall. Kauri varnish is designated as 8 K., an 8-gall. Zanzibar as 8 Z., an 8-gall. Manilla as 8 M., and so on.

To make what are known as enamel paints, certain pigments are ground in these varnishes, and it was thought desirable to ascertain what effect the character of the pigment has on the durability of the paint. Hence, in some cases, flake white, which is pure white lead, was used; in others, white zinc; and in others, pigments thought to be chemically inert, as ultramarine blue and chromium oxide, and also a very permanent red pigment known as flamingo red, the exact composition of which is not known.

Inasmuch as it has been believed that the process of baking adds to the durability of these coatings, in most cases duplicates were prepared, one of which was baked and the other allowed to dry at the ordinary temperature.

Besides these varnishes and enamel paints, plates were coated with ordinary red lead in oil, with two kinds of iron oxide paints in oil, with an iron oxide paint mixed in a shellac compound after a formula furnished by Naval Constructor Bowles, with ivory black in japan, with Edward Smith & Company's "Durable Metal Coating," which is a varnish in which a considerable amount of gilsonite has been sub-

stituted for resin, and with the "Sabin Process" enamel, which has been used on some of the most important hydraulic work done within the past few years. It is hoped that a careful study of the effect of sea water on these various coatings, part of which were applied to steel and part to aluminum plates, will lead to important advances in the knowledge of the subject.

The steel plates used were ordinary boiler steel about $\frac{3}{16}$ in. thick, purchased from a well-known firm of boiler makers. In all cases where two steel plates were coated with the same preparation, the one bearing the odd number was dried at the ordinary temperature and the one bearing the even number was baked at a temperature of 215° to 240° Fahr. for four hours or longer; except that all the "Sabin Process" pipe coating enamels were baked two hours at 400° to 450° Fahr. Each plate was stamped with a number before coating. The following table gives the coating applied:

STEEL PLATES.

No.	Coating.
1 & 2	Flake white in 20 K.
3 & 4	Flake white and white zinc, equal parts in 20 K.
5 & 6	White zinc in 30 K.
7 & 8	White zinc in 20 K.
9 & 10	" " in 12 K.
11 & 12	" " in 8 K.
13 & 14	" " in 30 M.
15 & 16	" " in 20 M.
17 & 18	Flake white in 8 M.
19 & 20	White zinc in 30 Z.
21 & 22	" " in 20 Z.
23 & 24	" " in 8 Z.
25 & 26	Flamingo red in 20 K.
27 & 28	Ultramarine blue in 20 K.
29 & 30	Chromium oxide in 20 K.
31 & 32	Durable metal coating.
33 & 34	" " "
35, 36, 37 & 38	"Sabin Process" pipe coating enamel.
39	Ivory black in japan.
40	Red lead in oil.

41 ..... Prince's metallic paint (oxide of iron) in oil.
42 ..... Purple oxide of iron in oil.
43 & 44 ..... No pigment, 8 K. varnish.
45 & 46..... No pigment, 12 K. varnish.
47 & 48..... " " spar varnish.
49 & 50..... " " 30 K. varnish.
51 & 52..... " " wearing body varnish.
53.... ..... Iron oxide in shellac mixture.
54..... Parahydric coating.

When these plates were removed from the water on July 29th, 1896, after six months' immersion, they were immediately inspected by Naval Constructor Bowles, Foster Crowell, M. Am. Soc. C. E.; William Barclay Parsons, M. Am. Soc. C. E.; Mr. S. V. V. Huntington, Manager of Edward Smith & Co.; James C. McGuire, Jun. Am. Soc. C. E., and the author. The plates were afterward removed to the author's laboratory, and, after an interval of a month, were carefully examined, with the following results:

1. Good; first-rate condition.

2. Good, but some small marginal blisters. No corrosion.

3 & 4. Like 1 and 2. Coating could be peeled off with a knife when first taken from the water.

5. Very thin near the edges; some marginal blisters.

6. Same; coating brittle where very thin, elsewhere tough; no corrosion.

7. Like 5. Fifteen or twenty small rust spots where the coating was very thin. Brittle.

8. Good condition; no blisters, but coating brittle; not easily scraped off when wet.

9. Hard and brittle, but not completely removed by scraping while wet. A large number of pin-hole rust spots on one side.

10. Good; no blisters, but hard and brittle, especially where thin.

11. Hard and brittle; no blisters; not easily removed by scraping while wet. The outer coat separated from the under coat when scraped, leaving the latter on the metal.

12. Some small blisters and rust spots on one side. Hard and brittle.

13. Hard and brittle, very many minute rust spots. General condition poor.

14. Could be completely scraped off with a knife when wet. Very little rust. Both 13 and 14 were tough and good where the coating was very heavy, brittle where thin.

15. Thin. General condition good, except along the margins, where there was some rust. Brittle.

16. Coating thicker on one side than the other. The thicker film gave good protection, but the other side was brittle and showed numerous rust spots.

17. Coating badly decomposed, the action taking place from the outer surface. Not much corrosion.

18. Some marginal blisters, but general condition pretty good; much better than 17.

19. First-rate condition, tough and adherent; not completely scraped off with a knife when wet; rather thin along edges.

20. General condition perfect, but could be scraped off when wet.

21. Good condition, but thin and brittle near edges; not easily completely removed.

22. Same, but coating could be scraped off when wet.

23 & 24. Thin, brittle, many rust spots; poor condition.

25 & 26. Many rust spots; general condition bad.

27. Not much rust, but many blisters; condition not good.

28. Better than 27, but very many small blisters.

29 & 30. About alike; very many small rust spots.

31 & 33. Some blisters along the margins where the coating was thin; elsewhere the coating was all right; could be scraped off when wet.

32 & 34. Same as 31 and 33, except that there was much more blistering along the edges. Not good.

39. Very bad; rusty all over.

40. A good many small rust spots, but no general corrosion. Coating considerably decomposed; could be scraped off completely, but not very easily. General condition fair.

All the pipe coating enamels were perfect.

Plates 41 to 54 were in a separate cage, which was destroyed by an accident after about three months' immersion, and all the plates were lost. This was very unfortunate, as these would have shown some well-known oil paints in comparison with the others, but the test will be repeated.

Thirty aluminum plates, coated with various paints and enamels, were removed from the sea water in the Brooklyn Navy Yard, July 29th, 1896, after immersion for six months.

The composition of these plates was as follows:

Series I.—Ninety-nine and one-half per cent. pure aluminum.

Series II.—Ninety-eight per cent. aluminum and 2% copper.

Series III.—Ninety-eight per cent. aluminum (the quality known as commercially pure aluminum).

Series IV.—Ninety-three per cent. aluminum and 7% copper.

Series V.—Seventy-five per cent. aluminum, 20% zinc, 3% copper, 1% iron.

These plates were numbered from 101 to 130, and were coated as follows:

I.	II.	III.	IV.	V.	
101	107	113	119	125....	"Sabin Process" pipe coating enamel, baked.
102	108	114	120	126....	Durable metal coating, one side baked.
103	109	115	121	127....	Ultramarine blue, one side; flamingo red, one side; ground in varnish, not baked.
104	110	116	122	128....	White zinc ground in varnish, one side baked.
105	111	117	123	129....	Chromium oxide ground in varnish, one side baked.
106	112	118	124	130....	Edward Smith & Co.'s spar varnish, no pigment, one side baked.

The varnish in which the ultramarine blue, flamingo red, white zinc and chromium oxide were ground was composed of 100 lbs. Kauri resin to 20 galls. linseed oil, thinned with turpentine. The chromium oxide was the anhydrous oxide made by the ignition method, and was of commercial quality, not chemically pure. The baked coatings were baked about four hours at 215° to 240° Fahr., except that the "Sabin Process" pipe coating enamel was baked two hours at 400° Fahr.

The condition of each plate is given in the following statement:

SERIES I.

101. Perfect.

102. Baked side, perfect. Unbaked side, three blisters ¾ in. diameter. No general corrosion or roughening. The surface of the paint had lost its gloss. The coating was good on the edges of the plates.

103. Ultramarine blue. Showed roughening of coating, numerous pin head blisters, no corrosion to speak of.

Flamingo red. General condition good, except near edges of plate, which showed blisters over a surface about half an inch wide and one-fifth the marginal distance; very little corrosion.

104. Baked side. About 2 sq. ins. in one place half covered with small blisters. No corrosion.

Unbaked side. First-rate condition.

105. Baked side, one blister, 1 x ½ in.; otherwise first rate. No corrosion. Unbaked side all right.

106. Both sides perfect.

SERIES II.

107. Perfect.

108. Baked side, one blister, ⅜ in. diameter.

Unbaked side perfect.

109. Blue and red about the same as 103, except that about twice as much surface was blistered. General condition good.

110. Baked side badly blistered in spots along the edges, amounting to about 6% of the total surface of the plate. Some corrosion under these.

Unbaked side all right, except that about 1% of the surface showed pin-head blisters along a strip about ½ in. wide on one edge of the plate.

111. Baked side showed four central ¾-in. blisters, numerous marginal ones about 1½% of plate. Very little corrosion.

Unbaked side in first rate condition.

112. Baked side, two central blisters 2 sq. ins. and 4 sq. ins., and nearly all the margin ½ in. wide. Considerable corrosion. Otherwise perfect protection and high luster.

Unbaked side, two central blisters ½ sq. in. and 1 sq. inch.

Slight marginal corrosion. Coating evidently thin on edges.

SERIES III.

113. At one corner evidently a break in the coating let in water and caused a blister of about 2 sq. ins. Coating rather overbaked and brittle; elsewhere perfect.

114. Baked side perfect.

Unbaked side tough and adherent, except one small spot near the middle of the plate, which looked as if the coating had been broken, and where corrosion had begun.

115. Blue and red about alike. No decided blisters, but coating itself showed some signs of decomposition, especially the blue, which had a rough surface.

116. Both sides in good condition, but showed some signs of incipient blistering about the edges.

117. All right on both sides.

118. Both sides quite perfect.

SERIES IV.

119. At several places about the corners of the plate single blisters, some of which were as large as 3 sq. ins., had formed. These appeared to be due to the fact that the coating was overbaked and had been cracked at the corners by the supporting framework, and galvanic action had ensued on the penetration of the sea water. This was facilitated by the 7% of copper in the alloy. The remainder of the plate was perfect.

120. Baked side showed three blisters of about 1 sq. in. each and some corrosion under these; otherwise all right.

Unbaked side perfect.

121. Blue and red about alike; about 30% blistered and corroded.

122. Pin head blisters along the edges; general condition all right.

123. Baked side all right.

Unbaked side, seven or eight small blisters, but no corrosion. General condition good.

124. Both sides badly blistered and corroded along the edge, about 10% of the surface. Where not blistered, all right.

SERIES V.

125. Coating brittle and certainly overbaked. Badly blistered along the edges. In all cases of blisters under pipe coating enamel, the blisters were continuous and start from the edge.

The middle of the plate was all right.

126. Baked side badly blistered along the edge, 6% or 8% affected. Unbaked side slightly blistered, chiefly along one edge; condition otherwise good. No corrosion.

127. Blue. Considerably blistered along the edges, in pin head blisters mainly. Little corrosion.

Red. About the same, but some large marginal blisters. The red had a smooth surface, but the blue was rough.

128. Baked side, nine or ten blisters of some size (1½ ins. diam.), and considerable corrosion. Remainder of surface good.

Unbaked side. About 1% of the surface, near the edges, with small blisters showing some corrosion. The rest of the surface all right.

129. Baked side. A large number of groups (about 1 in. diam.) of small blisters. No corrosion.

Unbaked side. About the same, but not as bad.

130. About like 124.

The pigment mentioned as flamingo red is supposed to be a mixture containing some coloring matter derived from coal tar, and is reasonably permanent in the air. In these tests it became dark and mottled.

The baked surfaces of those plates which had one side baked were in all cases harder and more glossy than the other sides, after the test was made. It should be observed, however, that while these coatings are all at present hard and firm, when they were first taken from the water they were much softer and could be more easily scratched or scraped off, with the exception of the pipe-coating enamel, which was exactly as it was when it was put in the water. Even the luster was not affected, and the smooth plates coated with it are like a mirror.

On all the plates, except those coated with pipe-coating enamel which was applied by dipping, the coating is much thinner for about an inch along the edges of the plates than it is on the central portion. This fact has been called to the attention of the workmen who painted the plates, and is said to result from the method employed in applying the paint with a brush. In future experiments, care will be taken to avoid this. Probably four-fifths of the corrosion occurred along this marginal strip.

The more nearly pure the aluminum, the less it seems to need protection. The series which contain large amounts of copper or zinc are the most difficult to protect; corrosion seems to progress rapidly when

the sea water gets the slightest admission, and it throws off the coating, no matter how impervious the latter may be.

These plates were suspended in an open oaken cage or rack, the plates being in a horizontal position, one above another, about 2 ins. apart. They fitted loosely in the rack, and each plate was supported at the four corners. The rack was suspended from a float, and was 6 ft. or so below the surface of the water.

In fitting these plates to the wooden frames, they were originally tight, but became loose as the water swelled the wood. In transporting them to the Navy Yard, putting them again in place, and the subsequent handling, it is quite possible that scratches may in some cases have been made in the coatings, which would account for some of the blisters on plates which were otherwise perfectly protected. Greater care will be given to these details in the future.

Other experiments indicate that there is probably considerable sewage in the water, as sulphides are present in appreciable quantity. Something in the water also discolored the white zinc used, but did not act except superficially.

White zinc appears to be the least acted on of any pigment used in this test. The durable metal coating gave excellent results. When first taken from the water, however, this coating was somewhat soft, though extremely tough and elastic, and could then have been scraped off. After drying, this was impossible.

The most satisfactory coating is the pipe-coating enamel, which was baked on; and it is probable that if it had not been for the accidental overbaking of some of the plates, a condition difficult to avoid in using a small oven though easy to regulate in a large one, all the plates thus coated would have been perfectly preserved. The other baked coatings did not do so well. It appears that an extremely high degree of elasticity is very essential in these tests.

In the foregoing notes, where it is said that there was "no corrosion," it is meant that there was no appreciable roughening of the metallic surface, which was bright when the paint was removed. Where corrosion is noted, it is meant that a deposit of oxide was found under the paint. In all cases of blistering there had been a little corrosion.

It is proposed to replace a considerable number of the plates, both steel and aluminum, for a further six months' test.

The author has at present no explanation to make of the results so far presented, but makes one or two suggestions. Charles B. Dudley, M. Am. Soc. C. E., has a theory that varnish is so constituted as to have a part of the oil which it contains in chemical combination with the resinous material, and a part of the oil free. If this theory is correct, it would be reasonable to suppose that the longer the oil and resin are heated together in the process of varnish making, and the higher the temperature employed, the more complete will be the combination of oil and resin, and the less free oil will remain. Now, for certain reasons it is not practicable to heat 8-gall. and 12-gall. varnishes nearly so much as 20-gall. and 30-gall. varnishes; and if one action of sea water is to dissolve the uncombined oil, it is plain that the varnishes which contain the most oil, but are most thoroughly combined, will suffer less than those in which the proportion of oil is less. This would explain the singular fact that while it appears both by these tests and by other and more general experience that a suitable combination of oil and resin has greater protective action than oil alone, yet the smaller the proportion of resin, the more durable the compound. It may be objected that oxidized linseed oil is itself a very permanent substance, but, while this is so, it is also true that it is easily dissolved by alkalies, and even by water containing ammonia, and it is quite possible that it may be rather easily soluble in sea water. Further experiments are needed on this point.

DISCUSSION.

Mr. Bowles. FRANCIS T. BOWLES, Esq.*—The speaker wishes to express his appreciation of the care taken by the author and his firm in carrying out the tests described in the paper. The greatest attention must be paid to the preparation of such plates in the first place, and to their subsequent immersion, care and inspection. For the last ten years the speaker has been in charge of docking, painting and cleaning the bottoms of ships, and during that time has made many experiments with plates. He found that conclusions drawn from experiments upon a series of plates did not agree with experiments with the same materials upon the bottoms of ships, although there was no apparent reason for this difference. Hence it is impossible to form definite, certain conclusions from any series of paint tests on plates, no matter how carefully they are made, even if they are distributed all over the coast in various kinds of water. The immersion of the plates at the Brooklyn Navy Yard is an indication of what would occur in other places. The water at the Navy Yard is very foul with sewage and the collections of the harbor, which fact serves to increase the apparent duration of the test by increasing the rapidity of the action of the paint.

It has been determined that good unpainted iron or steel plates will lose on one surface in 100 years from .30 to .50 in. thickness if immersed in sea water, .02 to .03 in. in pure, fresh water, and from .25 to .30 in. if exposed to the atmosphere. The problem of covering the bottoms of ships divides itself into two parts, the protection of the metal against corrosion, and the protection of the outer surface of this covering against fouling. The qualities of paint which prevent corrosion are apparently those making it water-tight. The paint must be elastic in order to provide for the changes of temperature and the strains to which ships are subjected when afloat. It must be strongly adherent to withstand the abrasion and usage ships receive in docking and alongside wharves. The qualities of paint which prevent fouling are those making it glassy, that is, a smooth, hard substance inert in air and water. Fouling has never been known to attach itself to clean glass, although if the latter be exposed to the action of water from which mud or slime will be deposited upon it, then marine growth attaches itself at once.

The subject of painting ships has attracted the attention of many people for a long period, one of the earliest patents, dating from about 1670, being for coal tar and asphalt varnish. The importance of the subject is shown by the fact that while the fouling of the battleship *Indiana* between her launching and trial was very slight, it was suffi-

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cient to make a difference to the builders of $100 000 in the premium earned for speed. It probably increased the resistance of the ship about 15 per cent. A painted vessel of ordinary size, after six months in the water, requires at least $1 000 for paint alone. A ship subject to ordinary service, staying in port about half the time will foul so rapidly that in from six to nine months there will be a loss of speed of from 25 to 40% ; where ships are running regularly and rapidly, the loss is less. Mr. Bowles.

The paints now used on bottoms of ships by the United States Navy Department are chiefly the McInnes, an English preparation, and the Rathjens, which is German, and these illustrate the two classes of paints generally employed for the purpose. The McInnes paint consists, first, of the so-called anti-corrosive paint, a pigment of iron oxide with a very quick drying vehicle and a small amount of oil. It dries very rapidly, a matter of commercial importance in reducing the time, and, hence, the fees of docking, On top of the anti-corrosive paint is applied copper soap, a thick, pasty, green substance, which dissolves slowly in sea water and forms salts poisonous to marine growths, thereby preventing their adherence to the surface. The Rathjens anti-corrosive paint is of the same character as that already mentioned, but the anti-fouling paint is a heavy, brown paint of which the pigment is largely oxide of iron. It contains a considerable amount of oil and certain insoluble poisons, which apparently choke marine growths, it being a peculiarity of soluble poisons that they will not affect the growth of barnacles.

Varnishes have seldom been used on the bottoms of ships, although various trials of them have been made. Their defects seem to be that their coefficient of expansion is not the same as that of metal, that they gradually disintegrate, and that water gets below them, destroying their adhesive power altogether, and causing them to come off in sheets and strips.

William Barclay Parsons, M. Am. Soc. C. E.—The packing of the plates in the crates and their subsequent handling undoubtedly injured the edges considerably more than the author has stated, as is apparent from an inspection of them. The ease with which many of the coatings could be removed when wet was noticeable. When taken from the water many were in such a condition that they could be removed in large strips by means of a sharp knife. When a coating was removed in this way, the metal below was bright in some cases, showing that, while the action of the sea water on the paint had been of a softening nature, there was no injury at all done to the metal below. The rust which is now so plainly observable on these bared spots has been caused by the action of the salt water reaching the metal after the removal of the varnished coating, as when these plates were examined they were still wet with salt water, having been just taken from Mr. Parsons.

Mr. Parsons. the river. This exception, of course, does not apply to the specific cases stated by the author, where some of the coatings had actually failed and allowed the water to penetrate and reach the metal. The speaker's observations at the time the plates were removed from the water convinced him that the "Sabin Process" coating was unquestionably the best.

Mr. Stiles. W. M. STILES, Esq.—In a pipe coating applied hot, the material not being thinned down with any vehicle like turpentine, it would be interesting to know whether its stable condition may not be due largely to the fact there is nothing about it to evaporate. There are no holes left in the film, such as are produced by the evaporation of volatile oils in most paints, which is shown quite plainly in some experiments relating to electric insulation. If a little water is placed on the paint so as to afford a large surface of electric contact, the current will pass readily through most coverings that are not baked or do not contain a large amount of resin, which seems to make a continuous, glossy surface.

It would also be interesting to determine whether the baking of the thin coat of oil and resin, asphalt or gilsonite has any greater tendency to unite the materials chemically than the heating in mass in process of manufacture. This is apparently true, judging from the action that takes place in thin layers of such substances when they come in close contact with the air.

Mr. Sherrerd. M. R. SHERRERD, M. Am Soc. C. E.—Experience with the asphalt coating on the steel pipes of the East Jersey Water Company indicates that there are substantially two coatings formed by the process used. The steel is first heated to about 300° Fahr., then dipped in asphalt at about the same temperature, and finally lifted from the bath and allowed to dry. This operation is repeated a second time. During the heating of the steel before it is dipped, an important change takes place on its surface, the rust being changed to a higher oxide by means of a lower oxide produced by the heat. The chemical equation for the change is $Fe_2O_3 + FeO = Fe_3O_4$. The Fe_3O_4 is the stable magnetic oxide. It is of a brownish color and approaches a pasty consistency. In uncovering some of the first Newark pipes protected with the asphalt coating, the latter was found to be intact. If scaled off, the brown paste was exposed, which remained unchanged when uncovered to the air for some weeks, indicating that further rusting of the steel seemed to be prevented.

Mr. Upham. R. D. UPHAM, Assoc. Am. Soc. C. E.—Experiments have been made under the speaker's direction for about a year past on a method of protecting iron ships from rust and from fouling in salt water. These experiments were conducted both on iron plates exposed to salt water and on a sea-going vessel. The material used was a compound of asphalt and copper filings, or copper in a finely divided condition, mixed

when hot, as asphalt paving mixture is prepared, and applied while still hot with a trowel, as a plasterer spreads plaster on a wall. When cold it forms a sheathing of great toughness and durability, and is sufficiently elastic to adapt itself readily to the expansion and contraction arising from changes in the temperature of the surface to which it may be applied. Mr. Upham.

Two principal objections to the use of copper for sheathing seagoing vessels have been the galvanic action which follows when copper and iron come in contact with salt water, which action destroys the iron, and the liability of water penetrating beneath the sheathing, thereby rusting the iron.

In these experiments the plate or vessel was first painted with a priming coat of pure asphalt to insure the perfect adhesion of the sheathing material. The asphalt in the compound then applied insulates each particle of copper from each other particle and from the iron. The coating was about $\frac{3}{64}$ in. in thickness, and presented a metallic surface, smooth and impervious to water. There has been no evidence of galvanic action, the surface of the sheathing composition was perfectly clean after four months, which was the longest test, and the iron showed no evidence of rust. In addition, the composition was in no wise affected by the water.

CORRESPONDENCE.

Mr. Crowell. FOSTER CROWELL, M. Am. Soc. C. E.—The experiments described in the paper cannot fail to awaken keen interest among those who have the care of structures exposed to sea water (including, of course, ships), and incidentally in connection with the general subject of painting metallic structures. The experiments, although not conclusive, pretty well establish in general the worthlessness of ordinary painting, as commonly practiced, for the protection of iron thus exposed, and the comparative values of the few descriptions of coatings that proved effectual, in a greater or less degree, in withstanding the effects of sea water.

The only tested preparations that appeared to come within the latter category were the "Durable Metal Coating," spar varnish, and the "Sabin Process" japan. All the others proved practically useless, and this was especially true of the coatings into which lead entered, the most worthless of all being that which is almost universally used at the present day for the painting of iron hulls, viz., a coating of red lead and oil. White lead was turned to a dense black from the sulphides in sewage present in the sea water, and very probably this same cause will account for the rapid destruction of the red-lead coating, which otherwise, as in pure sea water, might not have succumbed so readily or completely. The fact remains, however, that the experiments condemn the use of red lead in comparison with any other of the preparations tried.

Of the three coatings above mentioned as effectual, which word must, for the present, be taken in a comparative and modified sense, the "Sabin Process" specimens in all the classes showed much the best; so far as these experiments go, in fact, the plates of commercially pure aluminum appeared to have been perfectly protected by the japanning, the appearance of the plates containing alloys being less perfect. Generally speaking, the purer the metal, the more perfect the protection, which may be attributable to the fact that the alloys are means of producing electrolytic action.

The spar varnish specimens showed, at the time, the next best results, and these, too, were in a measure proportional to the purities of the plates. Recently the writer examined again a number of the same plates and verified the above conclusions, which had been reached by him at the time of first taking the plates out of the water. He found, on the whole, that the "Durable Coating" showed very much better, relatively, than it had, and seemed to divide honors with the spar varnish. As the latter had at first appeared to cling more tenaciously to the surface of the metal, the suggestion is made that a combination

of separate coats of spar varnish and "Durable Metal Coating" might prove more efficacious than either alone. Mr. Crowell.

Perfect continuity, inertness and durability are the essentials, and the writer is of the opinion, which would probably be shared by any one examining the varnished plates, that if the varnish coat be applied directly to the metal before corrosion occurs, and, after hardening, be covered with the "Durable Metal Coating," the best result attainable under ordinary conditions with the substances experimented on could probably be had. But this is not intended to convey the idea of superiority to the Japan coating baked on. It is only a statement of the writer's judgment, based on these experiments, as to the best results to be expected where the surface is such that baking cannot be resorted to.

Having had occasion, about a year ago, to study the subject of pile protection against the teredo in connection with a series of wharves built under his direction in the harbor of Charleston, exposed to sea water which is often in violent motion, the writer requested the author to furnish two examples of coatings for experiment. The coatings were not to be applied to the piles directly, but to sheet-iron pipes encircling the piles. Two test pipes were formed of common American sheet iron with riveted seams, the latter being not intended to be water-tight; one of the pipes was treated with the "Sabin Process," and the other with the "Durable Metal Coating." In each pipe a short section of an ordinary yellow-pine pile was placed concentrically, with an annular space of about 2 ins. all around it, which was filled with sand. The pile section was cut a trifle shorter than the pipe, so that two sheet-iron discs nailed to the ends of the pile section confined the sand tightly. The object of using the sand in the experiment was simply to reproduce the exact conditions under which it was proposed to apply the pipe covering, provided the desired coating could be found. The discs were purposely left uncoated in order to render the test as severe as possible, it being assumed that their corrosion in contact with the edges of the pipe might superinduce the speedy corrosion of the latter and that the effect would extend throughout the pipe. The specimens were then immersed in sea water in Charleston Harbor for a period of three months, being pulled up and examined from time to time, but, apart from that, kept constantly submerged. The first two months, January and February, were comparatively cold. It was reported to the writer that no signs of corrosion or deterioration of the coatings were visible up to March 1st. March was warm. Early in April he had an opportunity to examine them personally for the first time. Both specimens were found to be completely disrupted in that the coatings were loosened from the iron, and the iron was exposed to the full action of the water, while both coatings were useless for further experiment, the baked one appearing to

Mr. Crowell. be in a worse condition, if anything, than the other, for it could be detached in thin laminæ, like mica, in successive layers over the whole pipe; whereas, the other specimen, while wholly gone in places, leaving the metal bare, yet continued to cling in others, though soft and apparently liable to be washed off.

The experiment just described leads to two conclusions: first, that the temperature of the sea water is an important factor in corrosion; and second, that the character of the metal surface has much to do with the efficiency of the coating, the latter being more of a deduction than a conclusion, except when taken in connection with the experiments described in the paper.

The writer is pleased to learn from the author that the investigations are to be continued, and in warmer waters, where, too, pure sea water can be found, the water in the East River at the Navy Yard furnishing only special conditions of reaction. It may be that the effect of normal sea water may not prove as severe as the latter, but it is the writer's opinion that it will be more so.

Mr. Hobson. R. P. HOBSON, Esq.*—The valuable experiments described in the paper have a two-fold interest, as bearing upon the problem of preventing the corrosion of steel and the problem of preventing the corrosion of aluminum in sea water. The two problems, at the present stage, are essentially distinct. The one relating to steel has an industrial importance commensurate with the cost of maintenance of the bulk of the world's shipping, commensurate almost with the vast value of the shipping itself, affecting intimately the length of life of a vessel. But it is an older problem, and has been the subject of long and tireless research and experiment. The diversity of results, however, shows the problem to be still far from solution, a fact, indeed, universally recognized, and leaving open an important field for further research. The experiments in question introduce into the ranks of preventives the varnishes and enamels described and the process of baking. Their behavior in general appears to be excellent, particularly in regard to adhesion and impermeability, most marked in the test plates subjected to the baking process.

Resistance to the attachment of marine growths appears not to have formed part of the subject of investigation. It would be interesting in the additional experiments referred to if this feature were embraced, conditions being such that the plates would be covered with the usual marine growths. It would further be of interest to know the extent of the practicability of application of the promising baking process, whether it is necessarily restricted to small work, the process being applied after assembling. It would also be interesting to know the limitations imposed by cost for this process and for the varnishes in question, and also in what manner the baking process

* Naval Constructor, U. S. Navy.

secures its superior results, whether impermeability is reduced, while adhesion is increased. Mr. Hobson.

It is not in the bearing upon the problem of preventing the corrosion of steel, however, that the experiments have their greatest interest. Steel is already in general use for hull construction, and will continue in general use. The question of painting is only incidental, however important the incident; it is governed, and will continue to be governed, by the factors, maximum efficiency and minimum cost. The question of comparative results of different compositions is important, but it is not paramount.

With aluminum, however, the case is different. Its very use for marine purposes hangs on the practicability of preventing corrosion. It is not, at the present moment, so much a question of comparative processes, as one of the availability of any process.

When it is borne in mind that the natural field for aluminum is marine construction, where lightness is a capital requirement, particularly in naval construction, where economy of weight has a vital relation to military qualities; when it is remembered that in small construction, in the hulls of small craft, notably the types of torpedo boats and in hull fittings of all classes, the question of strength is secondary in determining the scantlings, the requirements of stiffness and the safeguard against penetration determining the limit long before the limit imposed by strength is reached, where, indeed, aluminum construction would realize the enormous saving of more than 40% over steel, with aluminum, too, of ready commercial production and reasonable cost; when these facts are borne in mind, and it is then considered that aluminum is barred from this wide and fertile field by the sole fact of its corrosion by salt water and salt air, some appreciation can be had of the importance of research and experiment in the direction of finding preventives.

Moreover, the serious condition which the first aluminum torpedo boat, built by Yarrow for the French government, was found to be in after a winter's neglect, the abandonment in consequence of the purpose of the French government to build of aluminum the five consorts of the first, all to be carried on the deck of the *Foudre*, and other torpedo boats of a similar type, these and other adverse incidents have given aluminum a serious setback abroad, while in the United States, similar unfavorable results in fittings, such as stanchion sockets, air port shutters, etc., on the torpedo boats built for the *Maine*, have confirmed the conclusion arrived at abroad, and aluminum is under a pronounced cloud of disfavor.

A careful examination of the facts will show that the general conclusion and impression are not warranted, though the action taken in the cases in question were probably expedient under the circumstances. The conclusion is in no sense final. Indeed, a comparison

Mr. Hobson. of the results obtained by the very limited scientific research for the prevention of corrosion of aluminum, with the results of the long, laborious and zealously pursued researches for the prevention of the corrosion of iron and steel in sea water, is wholly favorable to aluminum. The conflicting reports from different sources show the present stage to be still essentially experimental, and to pass unfavorably upon aluminum now would be to condemn without trial.

At the present moment a practical preventive of inadmissible corrosion has not been found, and, indeed, the adoption of aluminum would be unwise; but, as surely as day follows night, aluminum is to conquer a wide realm in marine construction. The experiments described are, then, of special value and interest at the present time of reaction.

Through the courtesy of the author, the writer had an opportunity of examining the test plates. He has also had occasion to examine the corrosion of aluminum in the yacht *Defender*.*

In connection with the present and future experiments, the following observations and suggestions present themselves:

Alloys.—The prominent result of the experiments is that which shows that the corrosion increases as the amount of alloy increases, and that copper, as the alloy, particularly accentuates the corrosion. This result is striking in the comparison of the excellent results of Series III, where the alloy was simply 2% of the commercial impurities, with the unfavorable results of Series II, where the same amount of alloy, 2%, was copper. The interest in this feature is special, for it requires an alloy to develop the best conditions for strength, while among the alloys suited to this purpose, copper is prominent, but is by no means exclusive. Moreover, it was a 5% copper alloy that was chosen on account of its high strength for the Yarrow torpedo boat, and it was from this most unfavorable alloy, exposed to most unfavorable conditions in Cherbourg Harbor, that the adverse conclusions referred to above were drawn.

It is evident that with two metals so widely removed in the electrochemical scale, the alloy of copper and aluminum contains within itself strong elements of galvanic action. Special interest would attach to the determining of the state of the copper in the alloy, and the intimate action that takes place, while it is evident that the alloy for marine purposes should be sought in metals not so far down the electrochemical scale.

Coatings.—The experiments, it is noticed, are restricted to varnish and enamel preparations. The favorable results indicate a field for these preparations for the preservation of fittings, if not for hulls.

* See report made to the Navy Department on her method of construction. This report, together with notes on the use of aluminum in naval construction, has been published by the United States Naval Institute.

Interest would attach to comparative tests of these preparations and those used on ships' bottoms, also with special preparations thus far made and that may be prepared especially for aluminum. A feature that suggests itself from these experiments is that the insulating qualities, as well as the porosity or permeability, may enter to affect results, and there would be interest in determining them in experiments to be made for comparative results. The generally unfavorable results with the baking process would indicate that the process increases the permeability, while the increase of adhesion counts for but little when galvanic action starts beneath. Interest also would attach to determining whether the paints themselves, or any of their components, enter into the phenomena. Mr. Hobson.

Conditions.—The close proximity of plates of different alloys which varied widely in their galvanic action, affected, in all probability, the results in the individual cases. As far as practicable, while still insuring the same conditions, plates of different alloys should be separated far enough not to affect each other. Even those of the same alloy, having the different coatings, should be arranged so as to affect each other as little as possible.

An analysis should be made as near as can be of the mean sample water of immersion, to determine the special agents, if any, that are present.

If practicable, sets of similar plates and coatings should be tested in different waters, and analyses of the water made in each case.

Both coated and uncoated plates, of the same and different alloys, should be immersed in vessels with sea water of sample kinds, and analyses, qualitative and quantitative, made as follows:

Of the materials of the plates before and after immersion; of the water before and after immersion; of the protecting coatings, where used, before and after immersion. These tests should be made progressively, analyses being made at regular intervals.

In addition, the tests should extend to determining the insulating properties of the coatings, and their permeability or porosity, in different thicknesses.

The object of the experiments outlined is apparent. They contemplate, while determining comparative qualities of different alloys and different preparations, to determine the phenomena that take place, and to find each element that enters and the role and relative degree of importance of each.

The writer has endeavored to have tests made by the chemist at the Navy Yard, New York, of corrosion taken from the *Defender*, and also of a sample furnished by the author of a corroded plate, together with the water in which the corrosion took place in a closed vessel, with a view of determining as far as the limited conditions permitted, what were the insoluble parts and what were the soluble products, and the

Mr. Hobson. parts they played in the phenomena. A sequence of unusual pressure of urgent current work has prevented the completion of these analyses, and the results thus far are unconclusive.

There is no doubt, however, that the scientific method of solving the important problem of preventing the corrosion of aluminum by sea water is to determine first the exact and intimate nature of the phenomena that take place, and then to proceed, with the knowledge thus gained as a basis, to find the means of prevention. The method is laborious, but the end sought offers large rewards.

Mr. Hastings. L. M. HASTINGS, Esq.*—As a part of the extensive addition to the Cambridge Water-Works begun in 1894, about 23 317 ft. of pipe, 40 ins. in internal diameter, was laid. A part of this pipe, 8 392 ft., formed the force main from the pumps to the reservoir, and 14 924.75 ft. was laid as a supply main connecting the reservoir with the center of the distribution system. This pipe was made of soft steel $\frac{5}{16}$ in. thick, in sheets about 7 ft. wide, and of a length equal to the circumference of the pipe. These sheets were riveted up in the usual manner, four sheets together, making a section about 28 ft. long. Each section was then coated with a preparation referred to in the paper as the Sabin coating. The pipe was manufactured and coated in the city, and was then transported on wagons to the trench for laying. The coating bore the abuse incident to teaming well, the injured portions being painted with two coats of what is now called "Durable Metal Coating."

In order to determine practically what effect water and the soil had on the material of the pipe, and also the value of the coating as a protective agent, a number of cast-iron, steel and wrought-iron plates were prepared for testing.

The plates were from 6 to 10 ins. square; the cast one about 1 in. thick, the plate iron and steel $\frac{5}{16}$ in. thick. Twelve of the plates were uncoated, twelve were given one coat of the Sabin coating, and four steel plates were given two coats of the same material. The reason why two coats were used on some of the plates was that in dipping and baking the plates, owing to their small size, the coating material seemed to drain off, leaving a very thin coating on the plate, and the two coats represented much more nearly the average coating as it was obtained on the pipe.

The plates were first carefully weighed by the sealer of weights and measures on his standard scales. Fourteen of the plates were then placed in the water at a gate chamber in the draught conduit leading to the pumping engines, so that when the pumps were in action, a constant stream of water was passing by the plates, thus subjecting them to the same influence as the interior of a pipe. The water taken through the conduit is a mixture of brook and pond water, of a fairly

* City Engineer, Cambridge, Mass.

PLATE X.
TRANS. AM. SOC. CIV. ENGRS.
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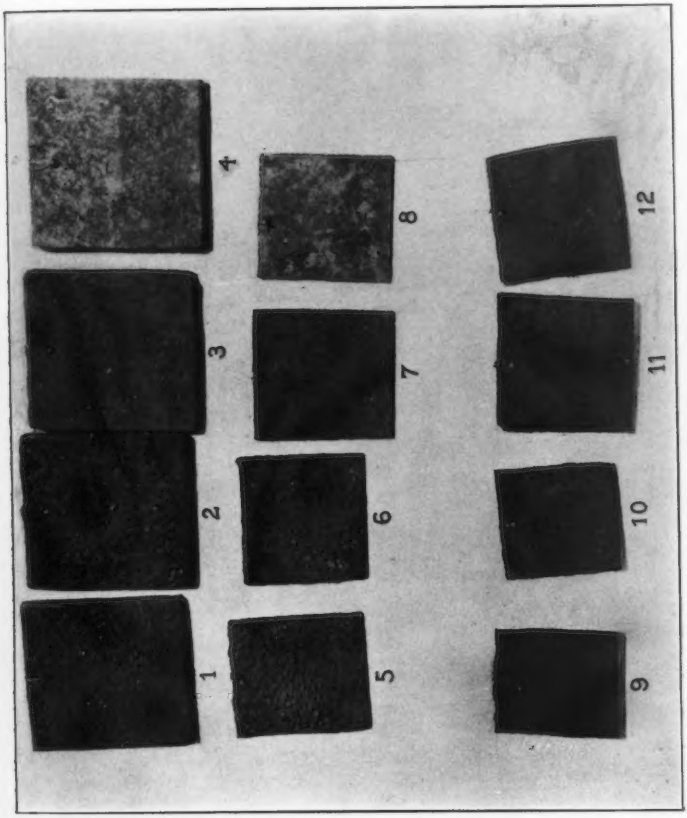
SABIN ON PROTECTION OF STEEL AND ALUMINUM.



TRIAL TESTS OF UNPROTECTED AND PROTECTED METAL UNDER VARIOUS CONDITIONS, AT CAMBRIDGE, MASS. Mr. Hastings.

Kind of metal.	Coating.	Situation of pipe.*	Original weight.	Weight when examined.	Percentage of increase.	REMARKS.
			lbs. oz. dr.	lbs. oz. dr.		
Iron.....	Uncoated.....	Water (5).	4 15 1	5 1 4	1.5	Badly tuberculated and rusted; worst of lot.
"	"	" (6).	4 6 12	4 9 0	3.1	Badly tuberculated and rusty.
"	"	Sand (7).	4 15 14	5 1 8	2.0	Very rusty; sand adhered to plate.
"	"	Clay (8).	4 5 10	4 6 4	0.89	Rusty.
Steel.....	"	Water (9).	4 7 11	4 8 8	1.1	Rusty and tuberculated, but not as badly as iron.
"	"	" (10).	4 5 0	4 6 8	2.1	Rusty and tuberculated.
"	"	Sand.....	4 5 6	4 5 12	0.54	Much rust.
"	"	Clay.....	4 9 3	4 9 8	0.4	Somewhat rusty.
Cast iron.	"	Water (1).	20 2 8	20 6 0	1	Badly rusted and tuberculated.
" ..	" . ..	" (2).	19 6 8	19 9 8	0.96	Badly rusted and tuberculated.
" ..	"	Sand (3).	19 10 13	20 0 4	1.7	Badly rusted; sand adhered to plate.
" ..	"	Clay (4).	19 13 10	19 13 8	.....	Somewhat rusty.
Iron.....	Single coat...	Water.....	4 14 11	.....	.....	In good condition; no rust.
"	"	" (12).	4 9 6	.....	.....	Good condition.
"	"	Sand.....	4 9 4	.....	.....	Fairly good condition; some rust spots.
"	"	Clay.	4 13 11	.....	.....	Good condition; little rust.
Steel.....	"	Water....	5 11 11	.....	.....	Fairly good; some little rust.
"	"	"	5 13 2	.....	.....	Fairly good.
"	"	Sand.....	4 11 0	.....	.....	Fairly good.
"	"	Clay.....	5 5 8	.....	.....	Fairly good.
Cast iron.	"	Water....	19 2 15	.....	.....	Fairly good; little rust.
" ..	"	Sand.....	19 4 6	.....	.....	Good condition.
" ..	"	Clay.....	20 8 2	.....	.....	Good.
Steel.....	Double coat..	Water (11)	5 11 13	.....	.....	In good condition.
"	"	" ...	5 6 8	.....	.....	Good condition.
"	"	Sand.....	7 2 12	.....	.....	Very good condition; bright and clean.
"	"	Clay.....	5 8 10	.....	.....	Very good.

* The figures in parentheses refer to the numbers of the plates shown in Plate X.

soft quality, and containing comparatively little acid. Seven of the plates were buried in a sandy soil, and seven plates were placed in a clay soil, all about 4 ft. below the surface of the ground.

The plates were placed in position September 14th, 1895, and were taken out for examination October 8th, 1896. Those which were covered with two coats of the material showed practically no change in appearance, being free from rust, and retaining in some degree their luster or glossy appearance. The plates which had one coat did not look quite as well as those with two coats; slight indications of rust appeared on some. The plates which were not coated at all

Mr. Hastings. presented a very different appearance, all being heavily coated with rust. Those placed in the water had numerous bunches of rust or solid tubercles on both sides. The plates buried in soil had more or less sand or clay adhering to the plates with the rust.

These plates were carefully reweighed by the same man on the same scales, and showed quite an appreciable gain in weight. The tabular statement on page 505 shows more in detail the facts concerning each plate, as far as the experiment has been carried.

While it is impossible to describe in detail the appearance of every plate, the results of this test may be fairly summed up as follows:

Metal covered with a coating of sufficient thickness was well protected from action of water. The thinner coating did not prove so efficient a protection, while unprotected metal, subject to the same influences, suffered considerably from oxidation and action of the water, the plate iron being affected the most, steel plate to a less degree, and the cast iron the least of all.

Mr. Sabin. A. H. SABIN, Assoc. M. Am. Soc. C. E.—Various questions have been addressed to the author which seem to require an explanation of certain points connected with these tests. One is, why were these three resins, Manilla, Kauri and Zanzibar, selected from the many sorts in use? All these resins are of vegetable origin, being exudations from trees; in no case, however, are these coniferous, so far as the author can learn. There are a few kinds of varnish resins which are used in the condition in which they are taken from the living tree; these are called recent resins, in distinction from fossil resins. The most largely used of these is Manilla, hence this was taken as a representative of this class. Next there is a class of fossil resins of comparatively recent origin, which are dug out of the earth, but were produced by trees of species still living. The resin which exudes from these trees is useless while fresh, but after it has lain in the earth a sufficient time, perhaps for centuries (nobody knows how long), it becomes hard and valuable. Of this sort the most common and typical is Kauri. Finally there are fossil resins so old that the trees themselves have become extinct, and of these the hardest and best known is Zanzibar.

There seems to be somewhat prevalent an impression that these investigations were undertaken with the idea of discovering a paint for ships' bottoms. This is a misapprehension, for the primary object is entirely different. There is much use, in the first place, for a coating for steel and other metals which will protect them from sea water and the moist air near the sea, such as bridges and piers, and metal pipes and other fittings, both on ships and shore; and in a much broader and more general way the author would point out that by immersion in sea water, especially when highly charged with sewage (as in this case) there is an opportunity of subjecting these coatings to extremely

severe conditions, which allow differentiation between them after a comparatively short test as thoroughly as after a test of several years in ordinary use, with the certainty that all are subjected to the same conditions. This is well illustrated by the fact that the plate with the red lead coating showed so great deterioration of the latter that it had practically lost its value. Now, this was pure red lead and pure oil, and three coats were applied in a more thorough and careful manner than is possible in ordinary work, and to a cleaned and bright surface. This plate would have been in good condition after a very long time if it had been exposed to pure country air, but the coating was practically destroyed during this test. This leads the author to remark on Mr. Crowell's statement that all but two of the coatings tried proved practically useless, which is by no means correct if it is considered that while they may be so for such an extremely severe exposure, though the author is not prepared to admit quite as much as that, some of them showed so much permanence as to encourage their use, not under water, but where they would be exposed to the moist and salt sea air, with, perhaps, occasional wetting, conditions which ordinary paints certainly do not stand well. He is sure that when the results obtained in this way are analyzed they are valuable. For example, the ribs, deck beams and fittings of yachts might be, even if of aluminum, protected in this way. Mr. Sabin.

In regard to the tests on sheet iron described by Mr. Crowell, it may be stated that one of the conditions, made necessary on account of cost, was that ordinary sheet iron should be used. As is well known, this is covered with several thicknesses of black scale, which is intentionally rolled in by the makers, and as it is much thicker on one side than on the other, it is impossible to remove it by pickling. As soon as the sea water obtained access to this scale it rapidly dissolved it, the chemical action going on between the oxide and the saline constituents of the sea water causing a mechanical disruption of the coating, which was no longer of any value. The baked coating came off in flakes, which remained elastic and continuous. The author does not know how to protect ordinary sheet iron under such circumstances, but he thinks if steel plates or beams, which have comparatively little scale, and that removable, were properly treated, the result would be satisfactory. He is now able to produce intentionally such effects as were shown by the baked coating, and to peel off films which show under the microscope a continuous backing of iron oxide, which may then be dissolved off by acid, leaving the film clean on both sides. This illustrates the importance of having a clean metal surface to paint on, a matter which cannot be too persistently reiterated.

The brown coating referred to by Mr. Sherrerd could hardly have been magnetic oxide, because, in the first place, magnetic oxide is black, and secondly, ordinary ferric oxide is not changed by heating

Mr. Sabin. at 300° Fahr. The author is inclined to think that it might have been a film of asphalt left on the surface, which always shows a brown color, but this is only a suggestion, as he did not see it.

The questions of Mr. Stiles as to whether the baking of the coating effects chemical union among the constituents is of much interest. The speaker has no doubt that it does. For example, the "pipe coating" material, before baking, is readily soluble in turpentine; after thorough baking, it is not softened by prolonged digestion in hot turpentine. It is known that chemical union occurs during manufacture, and its completion during baking doubtless aids to make it permanent. This, in part, answers one of Mr. Hobson's questions. There is no doubt that baking does increase both adhesion and impermeability, provided the coating is composed of materials which are capable of combination, and that the product is an elastic and not a brittle substance. This latter may be said to be in fact the result aimed at in all these experiments; to get a film which is insoluble and unattacked by any chemical agency liable to be brought against it, and tough and elastic, to resist mechanical injury or handling.

The increase of adhesion is probably due in part to the more complete removal of the air film between the surface of the metal and the coating, and this is one reason why a slow-drying coating is better than a quick one, a fact generally conceded. Mr. Hobson's conclusion that baking lessens permeability, the author does not agree with. While he admits that many of the baked coatings were unsatisfactory, it only shows, from his point of view, that these coatings were made of materials which would not stand the greatly increased chemical action produced by baking, and emphasizes the fact, previously realized by him, that making a suitable composition to be applied by baking, so as to get mechanical toughness and elasticity, combined with chemical inertness and permanence in the finished product, is the most difficult thing yet attempted in this kind of work. It seems to him that the pipe-coating material, when carefully applied to a good surface, is satisfactory; but none of the light-colored enamels are so.

He would further point out that no coating can be made which will resist severe abrasion. This should be borne in mind, especially with reference to aluminum. Suppose a coating could be made which would adhere as well as the zinc does in first-class galvanizing, and suppose the coating material as perfect as a film of gold or platinum; this would be generally agreed to be a perfect coating. But if a boat coated thus were to get on a rock, some of the coating would be scraped off. So it will be with anything that can be used, and it is necessary to bear these things in mind when considering the subject. It is one thing to paint steel, another to paint iron oxide, another to paint dirt; but besides all that, it must be remembered that the process is not making the metal incapable of corrosion, but only covering it with a film 0.002 to 0.005 in. in thickness of an inert substance.